PREVENTIVE MAINTENANCE OF SUSPENDER ROPES ON THE HONSHU-SHIKOKU SUSPENSION BRIDGES

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ABSTRUCT

Suspender ropes are members which hang girders from main cables along the whole length of a suspension bridge. If all suspender ropes are replaced, the cost will be enormous. Therefore we need to consider reduction of the Life Cycle Costs (LCC) of ropes by countermeasures of prolonging lifetime. On the Honshu-Shikoku Bridges, damage of ropes such as damage of paint, rust, heavy corrosion of anchorage-parts has been observed so far. Because the internal corrosion is not detected by the external appearance, the non-destructive inspection using the electro magnetic method has been adopted and the analysis of remaining lifetime was carried out. And the Honshu-Shikoku Bridge Expressway Company Limited (HSBE) is developing repair methods too. Those are: - a) the dipping technique on repainting of ropes, b) the Internal Filling Up Method and c) the Partial Replacement Method.

This paper presents a maintenance policy of suspender ropes of the Honshu-Shikoku Bridges especially repair methods.

1. INTRODUCTION

Ten suspension bridges exist in the Honshu- Shikoku Expressways, and among them, seven bridges have the CFRC (Center Fit Rope Core) type suspender ropes. The CFRC steel rope consists of a core strand, inner-layer strands and outer-layer strands and all strands are galvanized. The surfaces of ropes are painted. A set of four suspender ropes holds a panel point of girders from main cables at about ten meters intervals. The HSBE carries out visual inspections of suspender ropes once a year and found damage such as rust on rope and leakages of rusty water at anchorage-parts at the Innoshima Bridge. The bridge was opened in December 1983 and rust of ropes was found in late 1990'. At the Ohnaruto Bridge, heavy corrosion was found at anchorage-parts of ropes in 2000. The bridge was opened in May 1985 and is in severer corrosive environment than the other bridges. The majority of suspender ropes were in sound conditions, but only some

anchorage-parts were corroded heavily. To evaluate the condition of such suspender ropes, the HSBE studied electro magnetic method and developed non-destructive inspection devices for suspender ropes. And at the same time, the HSBE did disassembly tests of corroded ropes [1].

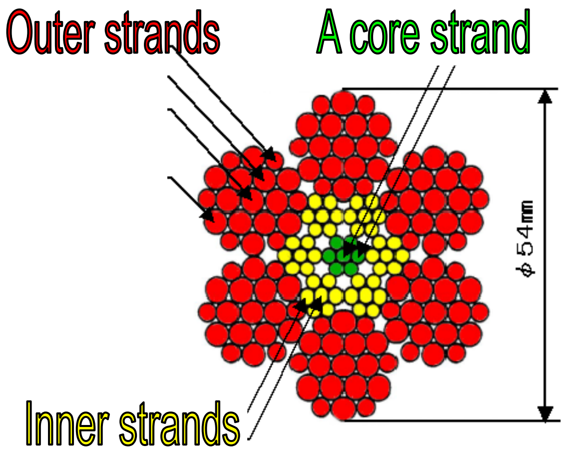


Photo 1. The CFRC type suspender ropes at the Innoshima Bridge

Figure 1. Section of the CFRC ropes at the Innoshima Br.

2. CORROSIVE CONDITION OF SUSPENDER ROPES

Major defects of suspender ropes of suspension bridges are summarized as follows.

(1) Corrosion among the majority of suspender ropes: In case of the Innoshima Bridge, damage and rust of all rope surfaces were found. However internal corrosion was not detected by external appearance.

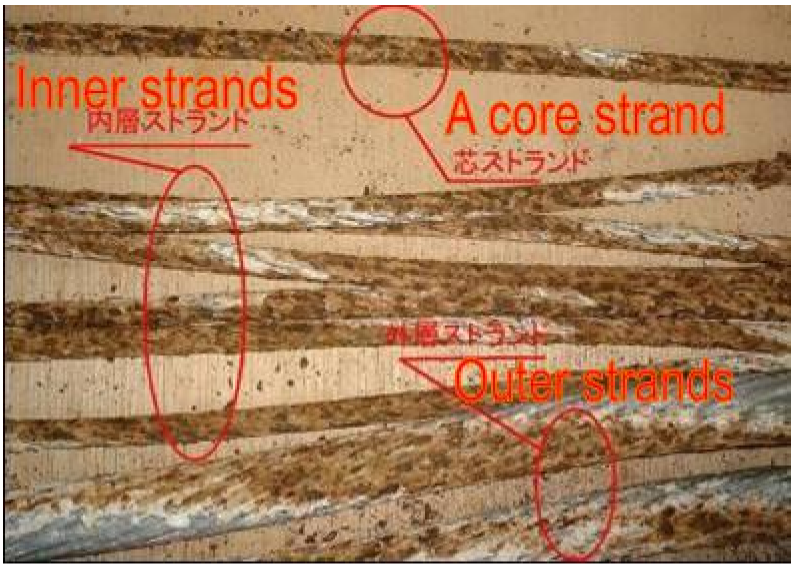


Photo 2. Surface condition of a suspender rope (Innoshima Bridge) (Left)

Photo 3. Internal corrosion of a suspender rope (Innoshima Bridge) (Right)

Therefore the HSBE started to evaluate internal corrosion of suspender ropes. The methods were, the disassembly test of actual ropes and the non-destructive inspection technique using electro magnetic method (Main Flux Method) [1].

Internal corrosion was found through disassembly tests of a suspender rope of the Innoshima Bridge. The test showed internal corrosion was not detected from its external appearance. Therefore the HSBE carried out site investigations of actual suspender ropes using Main Flux Method and measured actual decrease of the cross- sectional area of ropes. The results were, 1) Decrease of the cross-sectional area due to local internal corrosion exists along the whole of the rope. 2) Level of internal corrosion differs due to painting methods. Decrease of the cross-sectional area of the ropes which was painted by the dipping method is fewer than that of brush painting. And 3) the maximum 2% of decrease of the cross-sectional area was observed at the suspender ropes of the Innoshima Bridge [1].

(2) Corrosion of the anchorage-parts of suspender ropes: Severe corrosion of the anchorage-parts of ropes was found at the Ohnaruto Bridge. The location of the bridge is a channel where the Seto- Inland Sea meets the Pacific Ocean and the place is often attacked by typhoons and strong seasonal winds in winter. The basic design speed is 50 m/sec. (at 10m high, 10 minute average) and this is the highest speed among the Honshu-Shikoku Bridges. A chemical analysis of attached rust and dust showed the cause of corrosion were salt and exhaust gas.

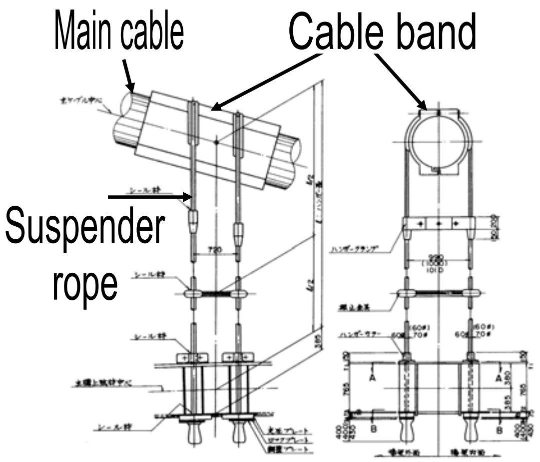


Photo 4. The whole view of the Ohnaruto Bridge (Left

Figure 2. Suspender rope system: the Ohnarto Br. (Rıght)

Photo 5. Anchorage of ropes (Left), Corrosion in a socket (Center), Close up view of a corroded rope(Right)

To confirm the condition of the Ohnaruto Bridge, four suspender ropes were removed and were investigated using Main Flux Method, tensile tests and disassembly tests at a laboratory. The test results were, 1) Decrease of the cross-sectional area of the great majority of suspender ropes was 0.5 – 0.8 %, it means the major parts were in sound condition. 2) However decrease of the area of the anchorage-parts was maximum 10.5 %. 3) Decrease of the tensile strength of ropes was maximum 29% for a loss of 10.5 % sectional area. 4) Breaking points of the corroded ropes at the anchorages were the mouth of sockets. According to the above mentioned results, we did a site investigation of ropes using non-destructive inspection technique, i.e. Main Flux Method. Then more severe corrosion at anchorage- part was found. The maximum decrease of the cross-sectional area was 15 %.

3. MAINTENANCE POLICY OF SUSPENDER ROPES

Through a series of investigation of the CFRC type ropes, the HSBE established a maintenance policy of suspender ropes [2]. 1) Basically countermeasures are aimed to have prolonging lifetime and are carried out at the early stage of corrosion. 2) Corrosion of the anchorage-part was more serious than other major parts; therefore a countermeasure for these parts is needed. A flow of maintenance is shown in bellow.

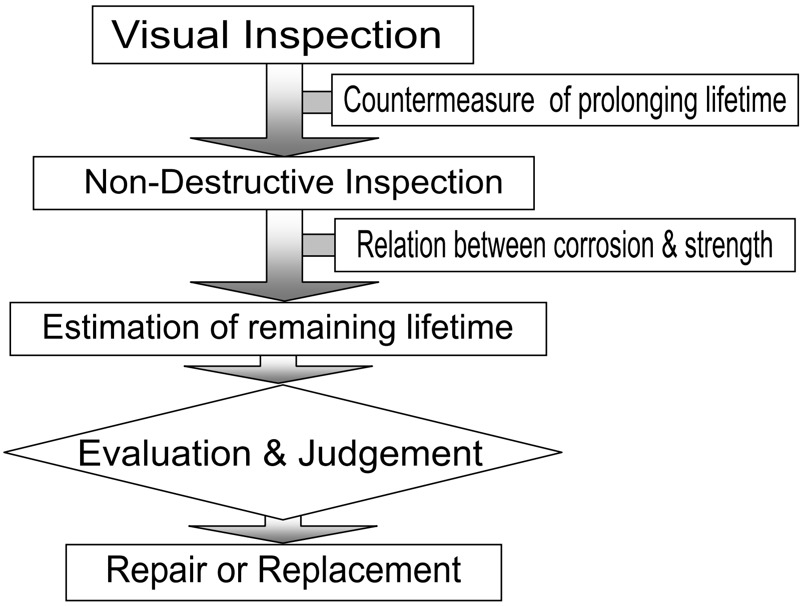


Figure 3. Flow of maintenance of suspender ropes

A countermeasure of prolonging lifetime is basically repainting. Repainting should be done by the dipping method. If corrosion of suspender ropes is observed, those ropes are checked by the non-destructive inspection. Then a remaining lifetime is analyzed too. Schematic repairs should be done according to those analyses. Repair methods of anchorage-parts are proposed as shown in the followings. 1) The Internal Filling Up Method: Voids inside rope are filled up by paste. Therefore intrusions of rain water from the upper part of ropes are intercepted. 2) The Partial Replacement Method: Because the great majority of ropes were in sound condition and have kept in use, only corroded anchorage-parts are removed and replaced.

4. ESTIMATION OF A REMAINING LIFETIME ON SUSPENDER ROPES

A remaining lifetime of suspender ropes was estimated by following procedure. Actual data were obtained at the Ohnaruto Bridge.

(1) The relationship between decrease of the cross-sectional area and decrease of the tensile strength: The decrease of the cross-sectional area was used the maximum value among a series of data. There is one assumption: A speed of corrosion is direct proportion to the periods. Therefore a forecast of a remaining lifetime of a suspender rope is done as shown in followings: - First, a decrease of the cross-sectional area is calculated by the following equation.

$$\frac{\Delta A}{A} = \frac{\Delta A_M / A}{M} N \qquad \text{Equation (1)}$$

Where、A : Cross-sectional area of rope in sound condition

ΔA : Decreased area of cross- section of rope at N years

ΔA_M : Measured maximum decreased area at M years had passed

(Assumption of the Ohnaruto Bridge: Corrosion started after 3 years from its opening, hence, M= 16 years)

N : A period (year) from starting of corrosion

A relationship between the cross-sectional areas and the tensile strength is shown in figure 4. Both axes' show rates of losses from a rope in sound condition. The thick line (with ○) shows the data of the CFRC ropes. The fine line (with △) shows the data of a strand rope which is given by a rope manufacturer. Results shows: 1) The decreased rate of the tensile strength is bigger than the rate of loss on the cross-sectional area. 2) The decreased rate of the strength of the CFRC suspender rope is bigger than the strand rope.

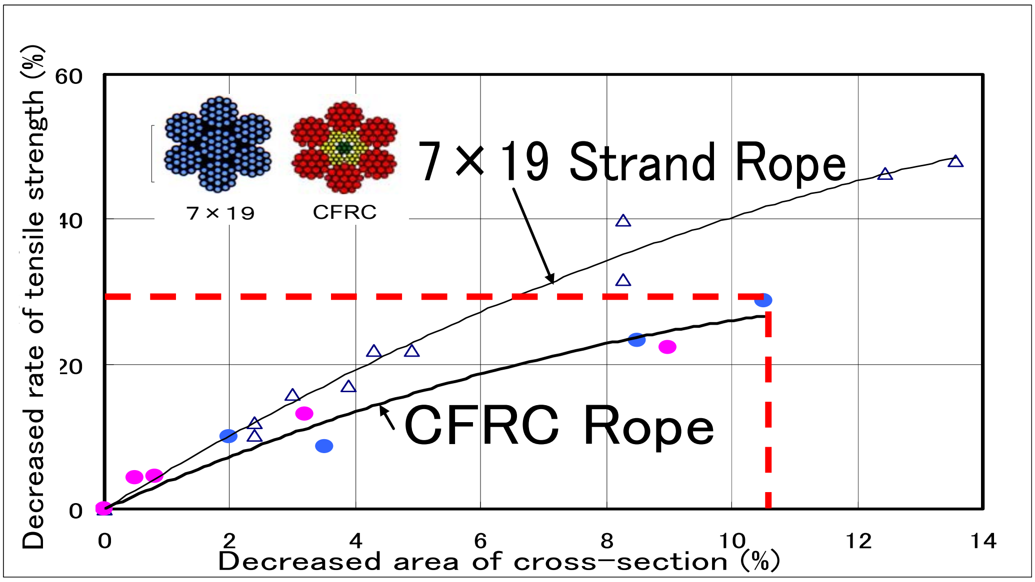


Figure 4. A relationship between the cross-sectional areas and the tensile strengths on corroded ropes

A relationship between a decreased rate of cross-sectional area ΔA/A of the CFRC rope and a decreased rate of the tensile strength ΔT/T were given by the following equation:-

$$\frac{100\Delta T}{T} = \alpha\left(\frac{100\Delta A}{A}\right)^{\beta} \qquad \text{Equation (2)}$$

Where, T: Tensile strength of rope in sound condition

ΔT: Reduction of tensile strength of the rope with decreased area ΔA

α, β : Constants of a formula

The above relation was confirmed through a series of tests of the Ohnaruto Bridge, and the constant values were roughly α=5.8 and β=0.62.

(2) Prediction of a remaining lifetime: We put Eq. (1) into Eq. (2), and get a reduction of the tensile strength according to the target year, then we get the safety factors S.F at the target year from an initial Safety Factor F_0.

$$S.F = \left(\frac{T - \Delta T}{T}\right)F_0 \qquad \text{Equation (3)}$$

The following diagram was a case study of a suspender rope of the Ohnarto Bridge using actual strength and the original safety factor (Fo=5.6). In this case, if we do not take action for a future protection of the anchorage-parts, an actual safety factor will drop less than original design in the future. The remaining lifetime is defined up to the time that the safety factor becomes lower than the minimum safety level.

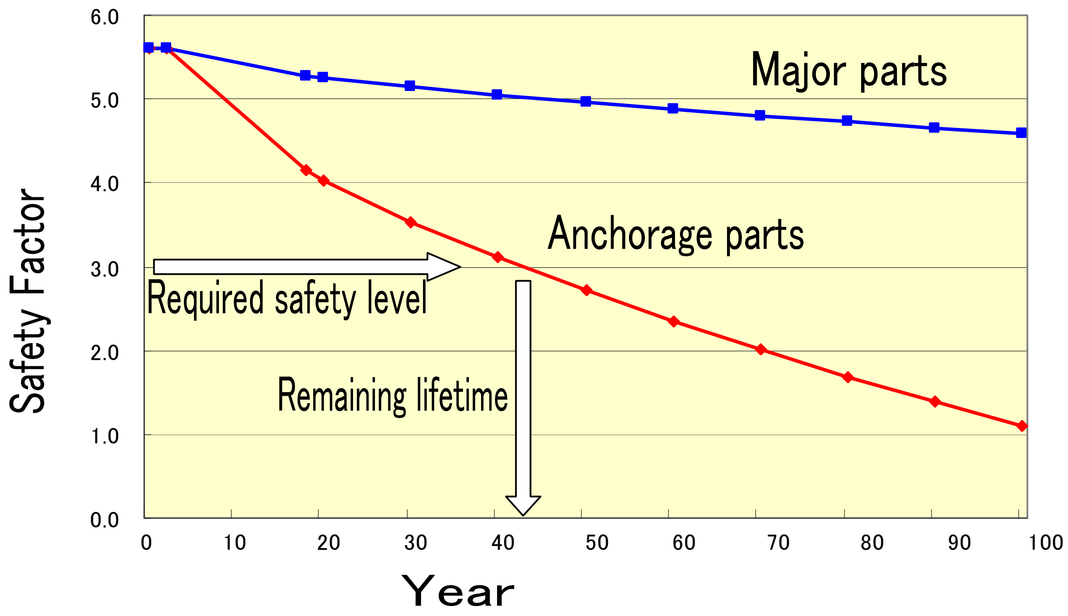


Figure 5. Prediction of the lifetime of suspender ropes as a case study

5. REPAIR BY THE INTERNAL FILLING UP METHOD AT ROPE ANCHORAGES

When corrosion is observed as an early stage and is found in progress at anchorage-parts of suspender ropes, we are planning to adopt the Filling Up Method (FUM) for a countermeasure of the prolonging lifetime. An outline of the method and the procedure are shown in followings:-

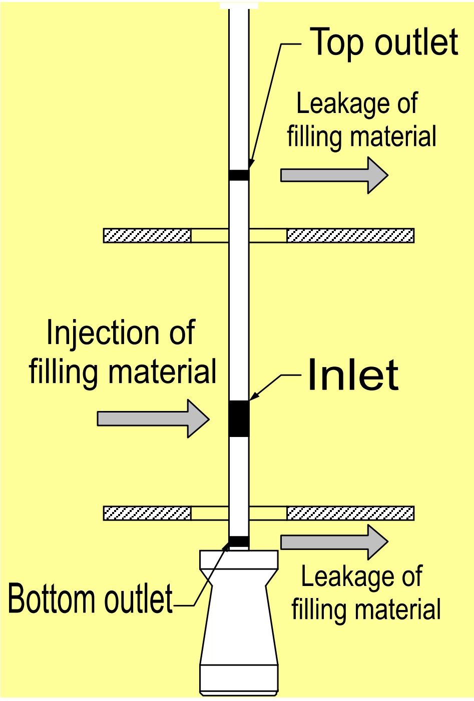


Photo 6. Works on filling up at an anchorage

Figure 6. The Filling Up Method (FUM)

When the method is adopted appropriate viscosity and pressure of filling-materials, leakages of material are found in about 10 minutes at the top outlet and about 1 minute at the bottom outlet if a strand is not choked by rusts.

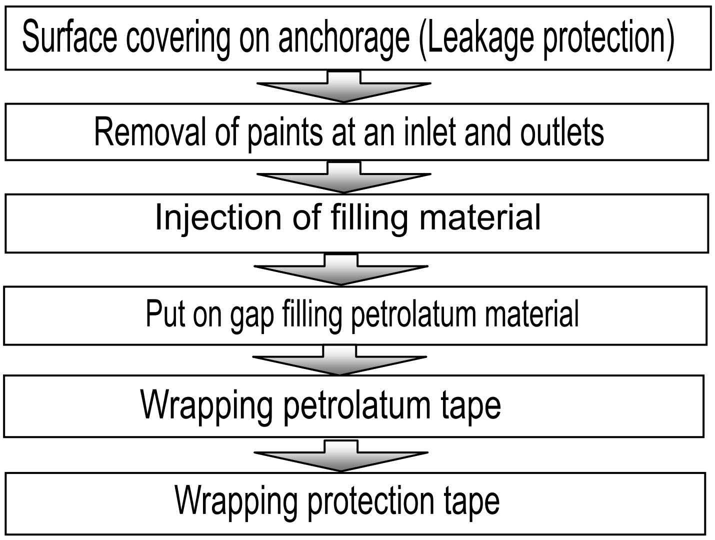


Figure 7. Flow of the IFU

During the development stages, laboratory tests were carried out to check whether the filling- material had filled all voids of ropes. A new rope was used to check injection of the filling-material and was disassembled. Finally all voids inside a rope were confirmed to be filled by the injection.

The repair materials and the method are requested to have the following properties: 1) Intrusions of corrosive materials are blocked, 2) each material should be an inhibitor or an electro chemical protection, 3) an internal filling-material can be injected and filled all inside voids of ropes, 4) an internal filling-material can keep long-term elasticity, 5) the method has good workability at anchorage-parts of suspender ropes. After researches on several methods, finally the petrolatum paste was selected as an internal filling-material as shown in the next.

Table 1. Specification of the IFU repair of suspender rope

Internal filling-material	Cleaning	Base court	Middle court	Top court
Petrolatum paste	3^{rd} grade	Gap filling petrolatum material	Petrolatum tape	Protection tape

The HSBE are planning to adopt this method as a countermeasure of prolonging lifetime and reduce the Life Cycle Cost of maintenance of suspender ropes. Actual condition after repair is shown in photo 7.

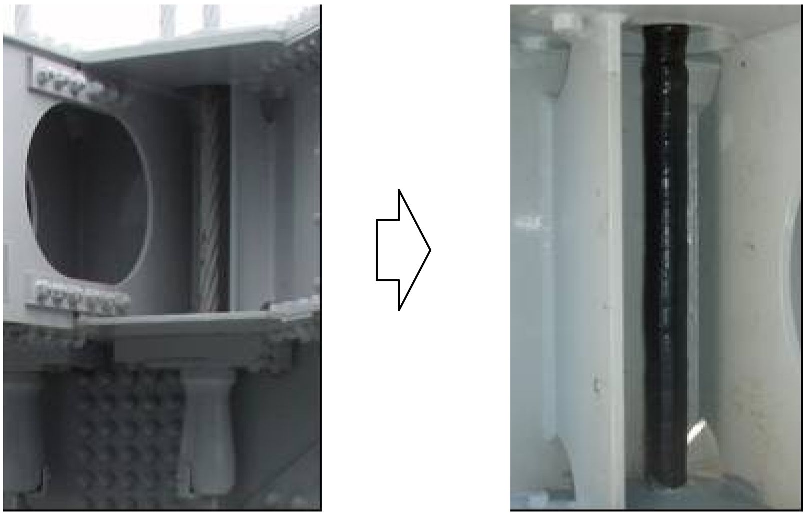


Photo 7. Repair by the IFU, before (Left) and after repair (Right)

6. REPAIR BY THE PARTIAL REPLACEMENT METHOD

When heavy corrosion is found at anchorage-parts, those parts may need to be replaced. In this case, the Partial Replacement Method (PRM) is a choice to be adopted. The PRM is to cut damaged parts out including ropes and sockets and to connect new anchorage-parts to the majority of existing ropes. The Sleeve Joint and Rod System is a selected method because it has no internal voids and it can be easily maintained. In this method, structural reliability and safety of connection between existing ropes and new anchorage are important. To select the methods, the HSBE studied three types of possible connections. One alternative was a connection

using metal edges and the other was a system using new socket and it holds an end of existing ropes with socketing metal. Technical features such as structural property, workability at sites, safety, and durability were compared and finally the method was selected. The system has adopted at architectural building already.

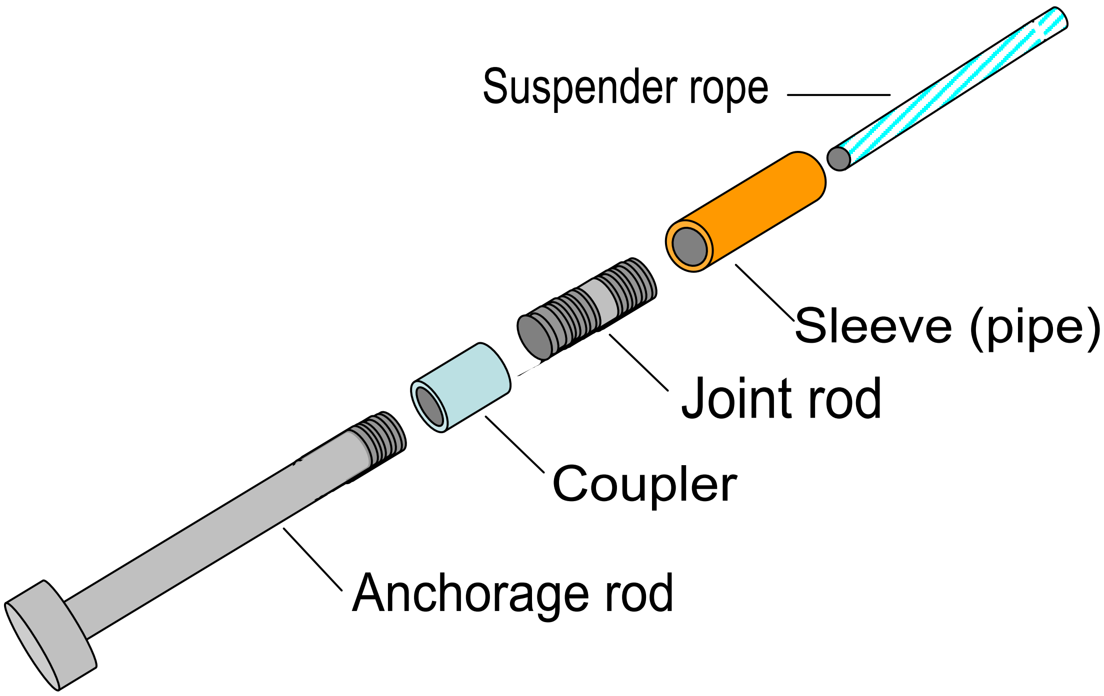


Figure 8. Sleeve joint system of a suspender rope (PRM)

The connection between a rope and a sleeve is done by the next steps: 1) The end of the rope is inserted into the sleeve, 2) Then the sleeve and the rope are squeezed through the whole length of the sleeve.

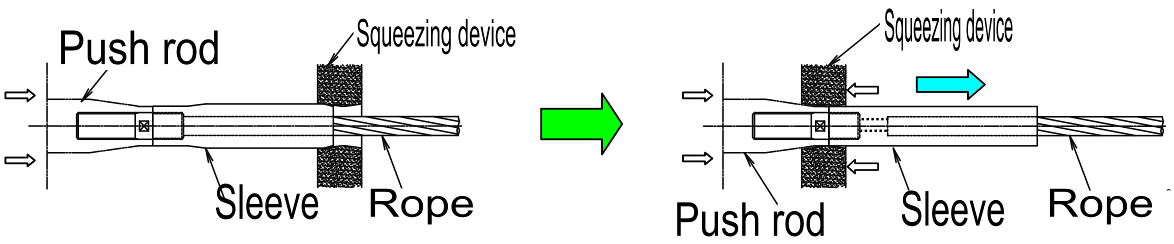


Figure 9. Mechanical squeezing of a sleeve pipe at the rope side

To confirm structural property, a cyclic loading test and a tensile strength test were carried out at a laboratory. The former was to confirm whether a rope was pulled out from a sleeve joint at actual loading. The result showed there were no slip out of the rope. The latter was to check the tensile strength of the joints when we changed sizes of the diameter and the length of sleeves. For adoption of the PRM, an experimental work was done at the Ohnaruto Bridge to confirm adaptability. Confirmation issues were, a series of procedure, workability, tension of suspender ropes and displacement due to the slipping out.

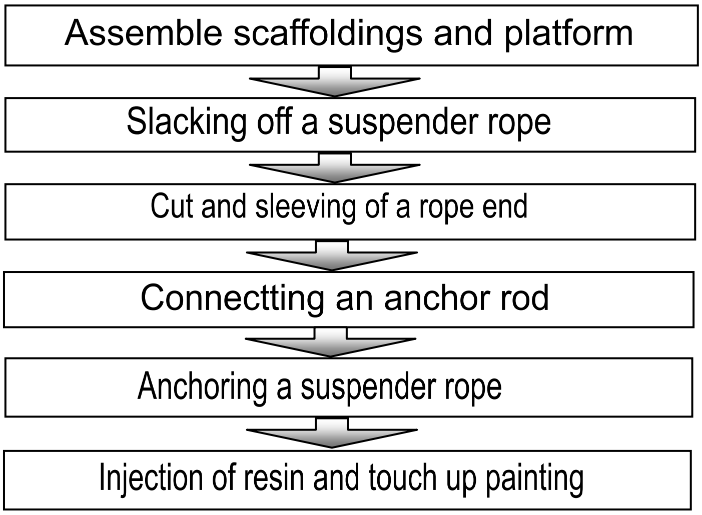


Figure 10. Procedure of the PRM

Photo 8. Assembling of a platform

Completion of the PRM is shown in Photo 9.

Photo 9. Partial replacement of a suspender rope (the Ohnaruto Bridge)

7. REPAINTING OF THE WHOLE SUSPENDER ROPES

A basic countermeasure of prolonging lifetime is repainting. Therefore repainting methods were developed.

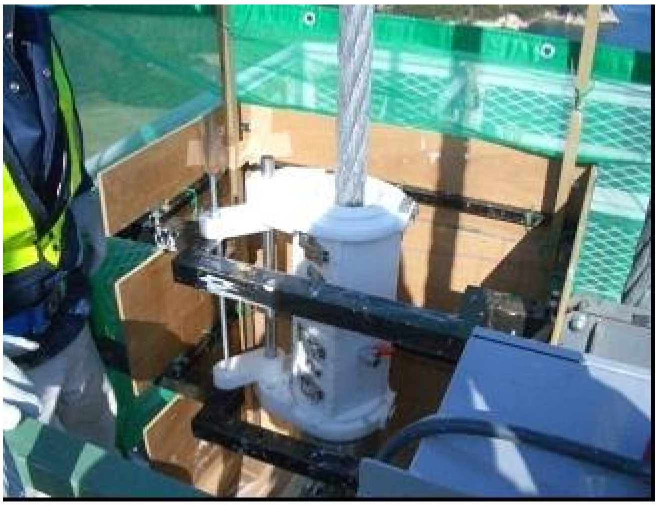
There are two types of repainting methods on suspender ropes. One is the blush painting and the

other is the dipping painting. The blush painting is a traditional method done by painters while the dipping painting is using a dipping machine which is like a container of paint and is moved along ropes by a winch. Finally the dipping painting was selected as a basic method. The reasons are, 1) Suspender ropes of the Innoshima Bridge were painted by the dipping painting and the brush painting. The dipping method was used for the center span and one outer span while the brush method was used for one outer span. To check the internal corrosion, the non-destructive inspection using the Main Flux Method was done for both painted ropes. Results showed the dipping painting was more sound condition than the blush painting [1]. In case of the Ohnaruto Bridge, the dipping painting has adopted for all suspender ropes, its condition was more sound than the blush- painted ropes of the Innoshima Bridge. 2) According to a surface observation, the coating film of the dipping painting has attached well on grooves of the external strands than the film of the blush painting. That means, the dipping paint has higher waterproof performance than the blush painting. At present, the dipping paint is two coats system.

Table 2. Specification of repainting of suspender ropes

Paint area	Cleaning	Base coat	Paint interval	Upper court	Dry thickness
Suspender rope (Dipping paint)	3rd grade	Flexible Epoxy Resin paint (110 μm)	1 – 7 days	Flexible Fluorine resin paint (25 μm)	135 μ

An adequate painting speed and the viscosity are issues to be checked before starting actual paint works. At present, the painting speed is given as 1.0 m/ min. The viscosity of paint should be adjusted depending on paint thickness and temperature.



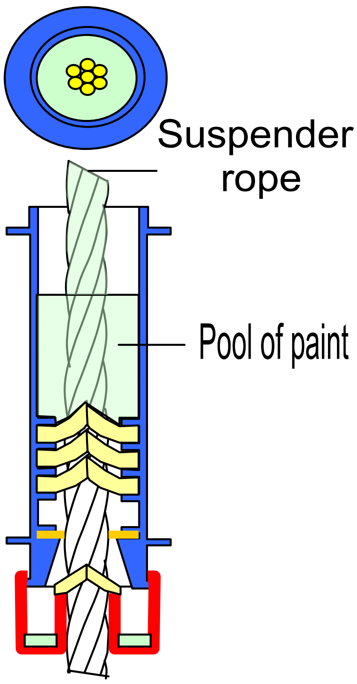


Photo 10. Dipping painting and the dipping machine (Left)
Figure 11. Cross section of a dipping machine (Right)

8. CONCLUSION

Suspender ropes of suspension bridges were considered as replaceable members in case of heavy corrosion and damage were found. However the replacements of ropes need enormous costs. Therefore reduction of the Life Cycle Costs is an essential policy. Annual visual inspection of the CFRC suspender ropes showed damages of ropes such as damages of paint, rust and heavy corrosion at anchorage-parts.

Internal corrosion is detected by the non-destructive inspection using the electro magnetic method (Main Flux Method). Losses of the cross-sectional area were the maximum 2 % for the Innoshima Bridge, the maximum 1% for the major parts and the maximum 15% for the anchorage-part of the Ohnaruto Bridge respectively. Correlation of the cross-sectional area and the tensile strength were utilized for an analysis of remaining lifetime of suspender ropes.

Repair methods of anchorage-parts are being developed. One method is the Internal Filling Up Method (IFU) and the other is the Partial Replacement Method (PRM). The former is adopted for early corrosive condition and the latter is for replacements of heavy corroded parts. The IFU is planned to utilize for prolonging lifetime countermeasure for the sake of the LCC reduction.

Repainting is an essential method, and the dipping technique using Fluorine Resin Paint is the most suitable method.

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